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Comparison of environmental and economic aspects of various hydrogen production methods

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Abstract

A wide variety of processes are available for hydrogen production from gaseous or liquid fuels. They differ according to the nature of the primary fuel used (ammonia, methanol, ethanol, gaseous or liquid hydrocarbons, water) and to the chemical reactions involved (decomposition, steam reforming, partial oxidation, electrolysis, gasification).

As recent technology progress makes hydrogen a realistic long-term energy option with little or no pollution, developments of new methods for its production and improvement of conventional technology are important. This paper analyzes the recent development of hydrogen production technologies followed by an overview of conventional and renewable energy sources and a discussion about enviro-economic aspects for hydrogen production methods. The results show that although renewable energy resources cannot entirely satisfy the energy demand but electrolysis associated with solar energy, wind power, hydropower and biomass are available renewable sources for significant hydrogen production.

Keywords: Hydrogen; Environmental and economical aspects; Pollution; Cost

Contents

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1. Introduction

Fossil fuel reserves are diminishing rapidly across the world, intensifying the stress on existing reserves day-by-day due to increased demand. Not only that, fossil fuels, presently contributing to 80% of world primary energy, are inflicting enormous impacts on environment. Climatic changes driven by human activities, in particular the production of greenhouse gas emissions, directly impact the environment. A secure and accessible supply of energy is thus very crucial for the sustainability of modern societies. There is an urgent need for a quick switch over of energy systems from conventional to renewable that are sustainable and can meet the present and projected world energy demand. Hydrogen, in the capacity of energy vector, is expected to be the optimum solution. It is a secondary form of energy, produced by using three different energy-supply system classes, namely, fossil fuels (coal, petroleum, natural gas and as yet largely unused supplies such as shale oil, oil from tar sands, natural gas from geo-pressured locations, etc.), nuclear reactors including fission reactors and breeders, and renewable energy resources (including hydroelectric power, wind power systems, ocean thermal energy conversion systems including biomass production, photovoltaic energy conversion, solar thermal systems, etc.).

At present, the global hydrogen production mainly relies on processes that extract hydrogen from fossil fuel feedstock as shown in Fig. 1. It can be seen from the figure that 96% hydrogen is produced directly from fossil fuels and about 4% is produced indirectly by using electricity generated through fossil fuels [1]. The largest consumption of hydrogen occurs in petroleum refining and in petrochemical industries for ammonia and methanol synthesis [2].

Most of the hydrogen is produced by steam reforming of natural gas (which is mainly methane) and other fossil fuels. Therefore, one would not be complete in a presentation of the various energy possibilities if the pollutional pros and cons were not considered. As concern increases about possible climate change and reductions in greenhouse gas emissions in response to the Kyoto protocol, ways of producing hydrogen without emitting CO_2 will be needed. It is therefore, important to consider the complete chain of processes for hydrogen production and usage, to find out whether greenhouse gas emissions would rise or fall by the substitution of hydrogen for other energy carriers [3].

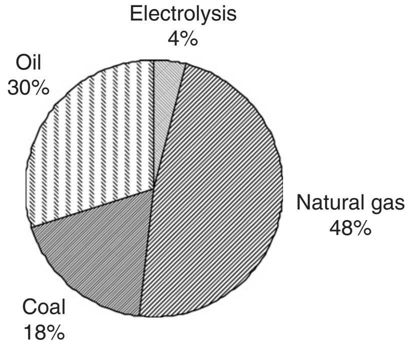

Fig. 1. Feedstock used in the current global production of hydrogen.

The environmental effect of hydrogen production by natural gas steam reforming, which is today the main path of production, is needed to be compared with the environmental effects of different production chains by the use of renewable energy sources. Significant progress has been reported by several countries including India in the development of hydrogen energy as an energy carrier and an alternative to fossil fuels [4]. The main objective of this paper is to present the sustainability assessment in terms of the environmental and economical aspects of hydrogen production technologies. The fuel systems (production and use) that are studied are the following:

(A) Hydrogen produced from conventional sources:
  (i) steam reforming of natural gas,
  (ii) partial oxidation of hydrocarbons,
  (iii) coal gasification.
(B) Hydrogen produced from renewable energy sources:
  (i) solar photovoltaic power for direct conversion,
  (ii) wind power,
  (iii) hydropower.

2. Environmental impact assessment of different process of hydrogen production

2.1. Hydrogen production from conventional sources

2.1.1. Natural gas steam reforming

At present, steam reforming is one of the most important and commonly used processes of hydrogen production. It is an endothermic, catalytic process carried out in the temperature range 970–1100 K and pressure up to 3.5 Mpa. Nickel is used as the catalyst. High hydrogen to oxygen ratio in the fossil fuels makes them better candidates for the reforming process. Mostly, natural gas is used as feed but heavier hydrocarbons up to naphtha can be processed. A significant amount of generated steam is not required within the system, so it is either exported directly or first converted into electric power by appropriate additional installations. The basic reaction is in two steps:

$$\mathrm{C}n\mathrm{H}m + n\mathrm{H_2O} \rightarrow n\mathrm{CO} + (n + m/2)\mathrm{H_2}, \tag{1}$$

$$CO + H_2O \rightarrow CO_2 + H_2. \tag{2}$$

A big disadvantage of the steam reforming processes is that the production of hydrogen is accompanied by the emission of large quantities of CO_2 into the atmosphere as it uses fossil fuels both in manufacturing process and as the heat source. Fig. 2 shows a block flow diagram of a relevant plant [5].

2.1.2. Partial oxidation of hydrocarbons

Partial oxidation of hydrocarbons is an exothermic reaction with oxygen and steam at moderately high pressure with or without a catalyst according to the feedstock and process selected. The second important process for production of hydrogen, it will accept all kinds of gaseous and liquid fuels and is therefore for processing high-boiling and high-sulfur raw materials such as heavy oil or petroleum refinery residual oil. The block flow diagram of a relevant plant is shown in Fig. 3 [6]. The basic reaction for partial oxidation of heavier hydrocarbon (Eq. (3) is

$$2CnHm + H_2O + 23/2O_2 \rightarrow nCO + nCO_2 + (m+1)H_2. \tag{3}$$

The disadvantage of partial oxidation process is that it also emits carbon monoxide along with carbon dioxide [7].

2.1.3. Coal gasification

The reaction mechanisms of coal gasification resemble very much with those of the partial oxidation of heavy oils. The basic reaction for gasification of coal is

$$CH_{0.8} + 0.6O_2 + 0.7H_2O \rightarrow CO_2 + H_2. \tag{4}$$

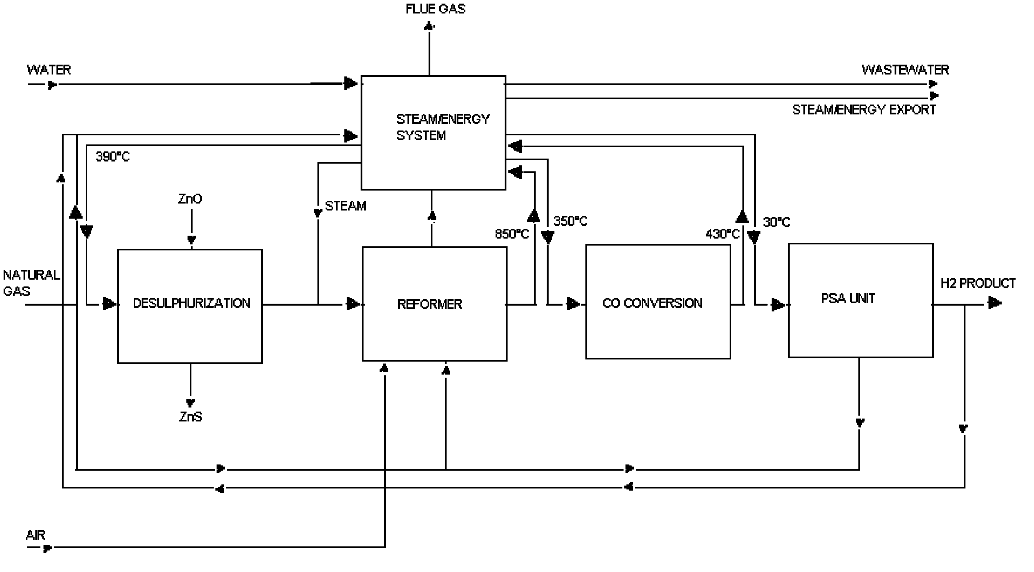

Fig. 2. Hydrogen production by steam reforming of light hydrocarbons.

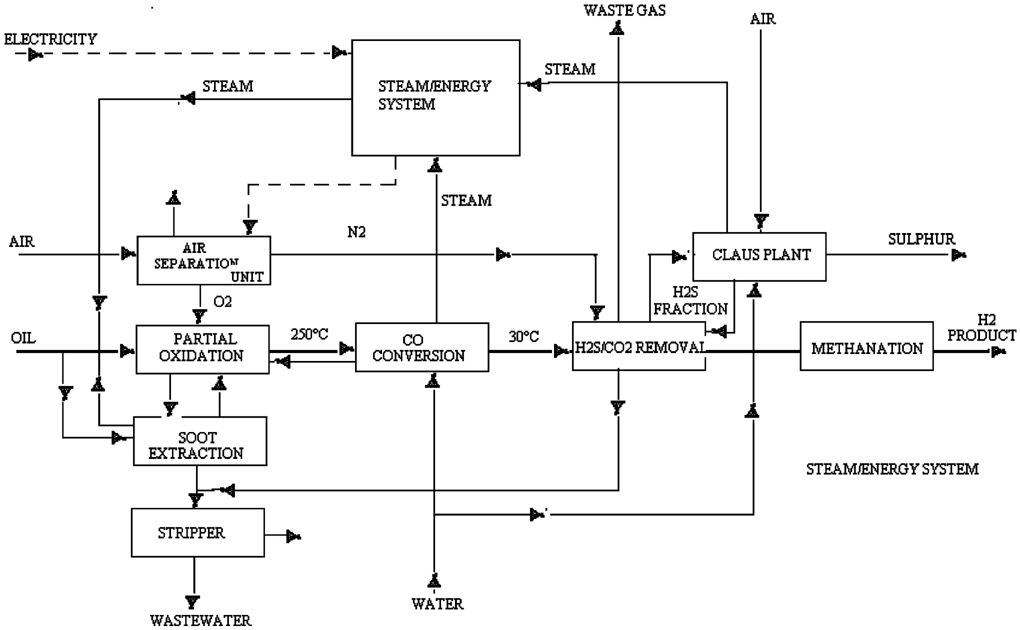

Fig. 3. Hydrogen production by partial oxidation of heavy hydrocarbons.

CO_2 is the most important greenhouse gas and is the largest emission from the systems [8]. Production of hydrogen from coal is carried out by two methods: (i) the synthane process and (ii) CO_2 acceptor process. When coal is reacted with steam at 450 psi and 800–900 °C, the gaseous products are CO, CO_2, and H_2. A small amount of methane is produced. The methane becomes a major product as the pressure is increased to 1000 psi. The CO_2 gas is removed from the final gas by washing monoethanomine or potassium hydroxide. The final gas is only 97–98% pure. CO_2 is a by-product. A basic flow sheet is depicted in Fig. 4.

The alternative process, called the CO_2, acceptor process, involves lime, which is introduced with coal when it reacts with steam. The produced CO_2 gas is removed by the lime as calcium carbonate. With the CO_2 removed, the shift reaction occurs in the main reactor, and this eliminates the need for an external shift reactor and the washing to remove CO_2 [9].

Using chemical Eqs. (1)–(4), the quantity of CO_2 emitted per kg of hydrogen production were calculated with different feeds and processes at 75% average efficiency and are tabulated in Table 1. Quantitative emission rate for sulfur oxides has been ignored because it is in negligible amount or nil when hydrogen gets from different processes and sometimes desulfurization step in the processes to remove sulfur.

2.2. From renewable energy sources

Hydrogen generated from renewable sources is likely to play an important role as an energy carrier in the future energy supply. Due to the finite life of fossil fuels and the global environmental damage caused by fossil fuels, the world has to switch gradually to

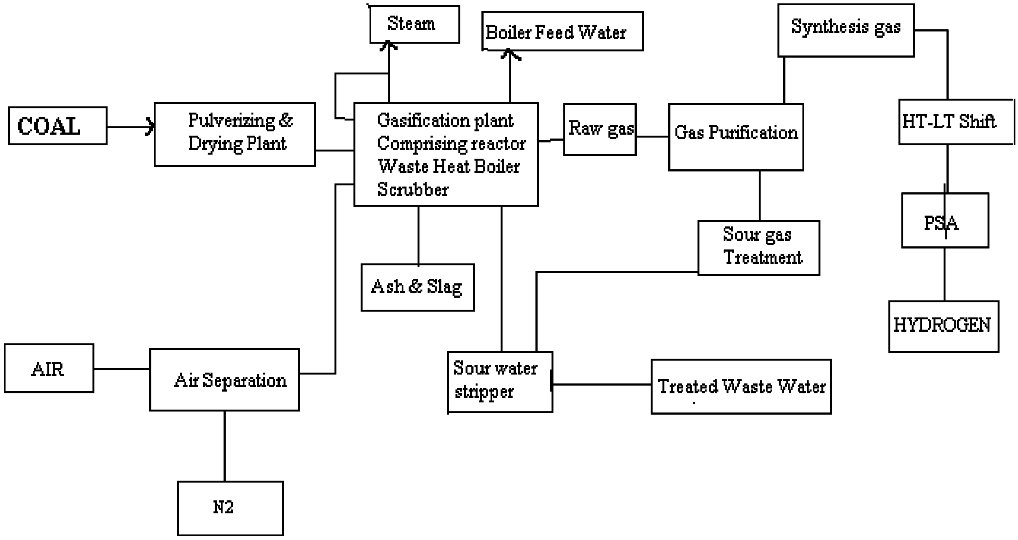

Fig. 4. Typical flow scheme for hydrogen from coal gasification.

Table 1
Production of hydrogen from different fuels and carbon dioxide emission

Process	Reactions	H_2 from H_2O (%)	CO_2/H_2 (Nm^3/Nm^3)	CO_2 and CO emission at per kg of H_2 production at 75% System efficiency	
				CO_2 (kg)	CO (kg)
Steam reforming + CO conversion	$C_nH_m + nH_2O \rightarrow nCO + (n + m/2)\ H_2$ $nCO + nH_2O \rightarrow nCO_2 + nH_2$				
From					
Methane	$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$	50.0	0.25	7.33	
Ethane	$C_2H_6 + 4H_2O \rightarrow 2CO_2 + 7H_2$	57.1	0.29	8.38	
Pentane	$C_5H_{12} + 10H_2O \rightarrow 5CO_2 + 16H_2$	62.5	0.31	9.17	
Naptha	$C_{10}H_{22} + 20H_2O \rightarrow 10CO_2 + 31H_2$	64.51	0.32	9.46	
Partial oxidation of hydrocarbons (heavier than naptha	$2C_nH_m + H_2O + 23/2O_2 \rightarrow$ $nCO + nCO_2 + (m + 1)H_2$				
From	$2C_8H_{18} + H_2O + 23/2O_2 \rightarrow$ $8CO + 8CO_2 + 19H_2$	5.3	0.42	12.35	7.85
Coal gasification	$CH_{0.8} + 0.6H_2O + 0.7O_2 \rightarrow CO_2 + H_2$	70	1.00	29.33	
Electrolysis (PV, Wind, Hydro)	$2H_2O \rightarrow 2H_2 + O_2$	100	0	0	

renewable energy sources such as water, wind and sun. Electrolysis is often considered as it is the only process that need not rely on fossil fuels; it also has high product purity, and is feasible on small and large scales. Electrolysis is responsible for the emission of carbon

dioxide only when power plants use fossil fuels to generate the needed electricity. Production of hydrogen from sustainable harvested biomass, solar energy, or wind energy might considerably reduce the production of emissions. However, distributed electrolysis using electricity from wind and solar energy could bring CO_2 emissions down to zero [10]. From all the above-stated discussions, hydrogen production from hydrocarbons is well established and most commonly used. Therefore, the focus of today's research is on hydrogen production through various non-hydrocarbon routes from which some are discussed below.

2.2.1. Solar photovoltaic power for direct conversion

Solar energy is a clean, renewable energy source and has attracted much attention as an alternative to fossil energy for future use. The various methods/process used are:

2.2.1.1. Photolysis. When water molecules absorb energy at a rate of 285.57 kJ/mole of water from ultraviolet radiation, hydrogen in principle can be released. Some photocatalysts are used to absorb visible light and transmit the energy of appropriate wavelengths and intensity of water molecule to liberate the constituted gases. The photolysis with a photocatalyst "X" can be expressed as follows:

$$H_2O + X + \text{Light} \rightarrow \text{Reduced } X + 2H^+ + \tfrac{1}{2}\,O_2$$

$$\text{Reduced } X + 2H^- \rightarrow X + H_2$$

$$H_2O + X + \text{Light} \rightarrow H_2 + 1/2O_2 + X.$$

The photocatalyst's X's are some compound salts, compound semi-conductors, photo-synthetic dyes, some intact cells of some species of blue-green, green and red algae, some photosynthetic bacteria, etc. This method (a) is direct, (b) uses ordinary light (c) delivers the photocatalyst back and (d) has very low efficiency.

2.2.1.2. Photovoltaic-electrolysis system. Photovoltaic cell converts sunlight directly into electricity. Photovoltaic cell and an electrolyzer are combined to create a device that generates hydrogen and is called photoelectrolyzer. The photoelectrolyzer is placed in water and when exposed to sunlight begins to generate hydrogen. The hydrogen is then collected and stored (Fig. 5). The electricity obtained through hydro, wind, wave, tide, ocean thermal and geothermal energy can also be used in the electrolysis process to get hydrogen. The basic arrangement to use for electrolysis is Hoffmann Voltameter apparatus, which is attached to electricity source described in our previous work [11].

2.2.2. Wind power

Hydrogen can be produced by electrolysis using wind turbines as the source of electricity. Of all renewable energy sources, using wind turbine-generated electricity to electrolyze water has arguably the greatest potential for producing pollution-free hydrogen. It is essentially emission-free, producing no CO_2 or criteria pollutants, such

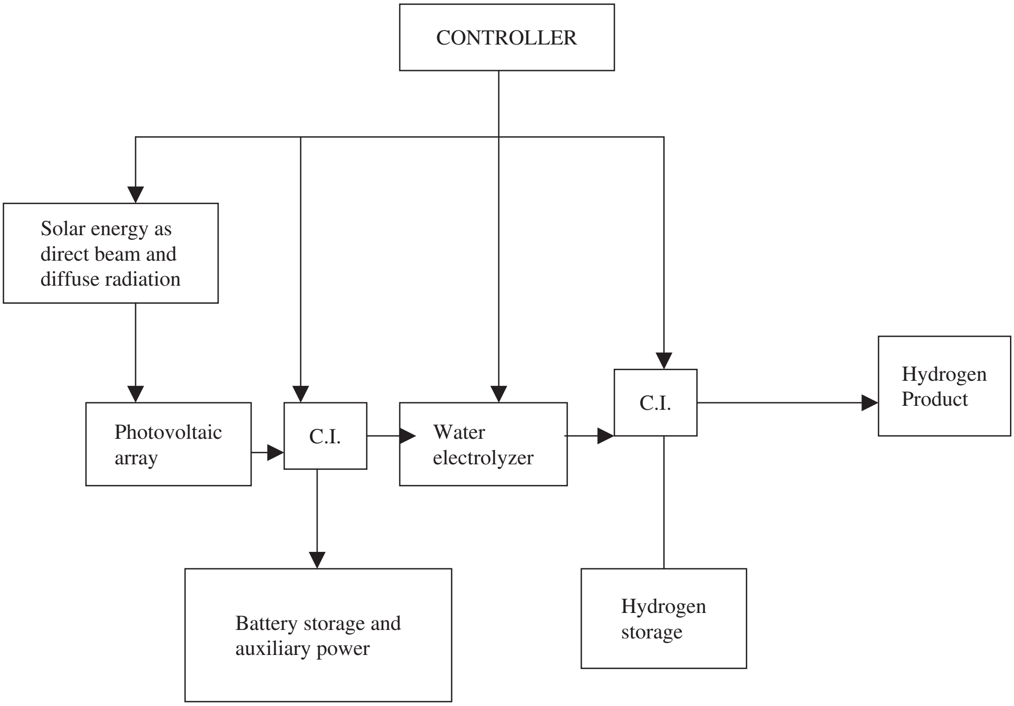

Fig. 5. Photovoltaic/electrolysis production system block diagram.

as oxides of nitrogen (NO_x) and sulfur dioxide (SO_2). But wind energy is not free of problems. There are environmental and technical issues that must be dealt with. Wind energy's most serious drawback continues to be its intermittence and mismatch with demand, an issue both for electricity generation and hydrogen production.

2.2.3. *Hydropower*

Electricity production from hydropower is also the source of hydrogen production. This electricity is further used in the spitting of water molecules to produce emission-free hydrogen.

3. Economical aspects

To complete the comparison among the different processes, the cost analysis was performed to determine the cost of hydrogen production per kg by a different process. The cost of producing hydrogen includes the capital, operation, maintenance and feedstock costs. The cost of per kg of hydrogen production is given by

$$C_H = C/H.t + M_y/H + C_F + E, \tag{5}$$

where the first term of RHS of Eq. (5) accounts for capital cost of the system, the second term for maintenance cost, the third term for feedstock cost and the last term for electricity consumption.

Table 2
A comparison of the cost of hydrogen from different processes

Process	System's efficiency η (%)	Hydrogen purity (%)	Capital cost (Rs in millions)	Maintenance and operational cost (%)	Running cost				Hydrogen cost (Rs./kg)
					Feedstock		Electricity		
					Qty. (kg)	Cost (Rs)	Units/Kg	Cost (Rs)	
(A) SMR	80	97	150	3	4.5	84.8	0.570	1.71	106.3
(B) Electrolysis	75	99.9							
PV[a,b] (35MW)		7000	2	NR*	NR	NR	NR	854.3	
Wind[b,c] (24MW)		1200	2	NR	NR	NR	NR	146.4	
Electricity									
Normal hours						52.6	157.8 (@Rs 3.00)	157.8	
Off-peak hours						52.6	73.64 (@Rs 1.40)	73.6	
Hydro power						52.6	105.2 (@Rs 2.00)	105.2	

*NR = not required.
**1 US$ = Rs 44.
[a]5 KWh/day/kW output and capital cost Rs. 200 millions/MW.
[b]Plant use factor 25% and capital cost Rs. 50 millions/MW.
[c]Only maintenance cost.

The term economic life relates to the reciprocal of the interest paid annually to cover it in view of the expected physical life of the system. The economic lifetime, t, of Eq. (5) is given by

$$t = \frac{+(1i)^n - 1}{i + (1i)^n}. \tag{6}$$

To calculate the economic life, the rate of interest, i, is taken to be 8% and the physical life (n) of hydrogen production system is considered 20 years.

Generally, the electricity boards divide the daily load pattern into three categories: (i) normal load hours, (ii) peak load hours and (iii) off-peak load hours. To improve the plant load factor of a power plant, the electricity boards provide lowest electricity tariff during the off-peak hours. The tariff rates for the year 2004–2005 are given in Appendix A.

The hydrogen production capacity of the plant was taken as 1000 MT per day and accordingly the required design parameters were considered and used in Table 2.

4. Results and discussion

A comparison for the generation of CO_2 by different processes is given in Table 1. It can be seen from the table that the emission of CO_2 varied between 7.33 and 29.33 kg of per kg of hydrogen production using conventional fuels at 75% system efficiency. The CO_2 emission by steam reforming is lesser as compared to partial oxidation of hydrocarbons and coal gasification.

It can be seen from the table that the CO_2 emissions associated with making hydrogen from coal are about 3 times higher than the hydrogen manufactured from natural gas.

In addition to CO_2, the other pollutants resulting from conventional combustion of coal are sulfur oxides (SO_x) and nitrogen oxides (NO_x) particulates but in very small quantities. It also reveals that the emission of CO_2 increases from light to heavy fossil feedstock. The CO_2 emissions are zero, if renewable energy sources like wind, solar and hydroenergies are used.

To determine the per kg cost of hydrogen, the parameters used in Eqs. (5) and (6) for steam methane reforming (SMR) and electrolysis process are given in Table 2. Using these, the cost of per kg of hydrogen was calculated and is also tabulated in Table 2. The cost of per unit kg of hydrogen by SMR process is Rs.106.3 and for electrolysis process is varying between Rs. 73.6 and 854.3 depending on the type of electricity generation system used. Though the production cost is minimum, if off-peak power is used in the electrolysis process, it would not be reducing the CO_2 emission. However, the utilization of off-peak power would lead to improved plant load factor and hence the reduction in $\mathbf{CO_2}$ emission. The utilization of hydropower for the production of hydrogen is coming to be more favorable in terms of cost and environment. If wind energy is utilized for the production of hydrogen, the cost of hydrogen is 2.0 and 1.4 times higher than the cost of hydrogen, if compared with off-peak power and hydroenergy.

So, electrolysis is seen as a potentially cost-effective means of producing hydrogen on a distributed scale and at costs appropriate to meet the challenges of supplying the hydrogen needs of the early generations of fuel cell vehicles. Electrolyzers are compact and can realistically be situated at existing fueling stations.

5. Conclusion

Analysis of enviro-economic aspects associated with present and advanced technologies for hydrogen production leads to the following conclusions:

- The utilization of off-peak power should increase to improve plant load factor and to take its economical benefits.
- Use of renewable energy especially hydro and wind energy are the favorable source of electricity for the production of hydrogen using electrolysis process in reference to pollution-free environment to get clean hydrogen.

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Appendix A

Electricity Tariff of a state for the year 2004–2005

Time	Category	Tariff
6:00 a.m. to 6:00 p.m.	Normal load hours	Rs. 2.15
6:00 p.m. to 10:00 p.m.	Peak load hours	Rs. 3.15
10:00 p.m. to 6:00 a.m.	Off-peak hours	Rs. 1.30

References

[1] Boessel U, Eliasson B, Taylor G. The future of the hydrogen economy: bright or bleak? Available online at ⟨http://www.efcf.com/reports/⟩, 2003.
[2] Pietrogrande P, Bezzeccheri M. Fuel processing. In: Bloman LJMJ, Mugerwa MN, editors. Fuel cell systems. New York: Plenum press; 1993. p. 121–56.
[3] Kuuskaraa VA, Pekot LJ. Defining optimum CO_2 sequestration sites for power and industrial plants. Proceedings of the 6th international conference on greenhouse gas control technologies 2003:609–14.
[4] http://www.mnes.nic.in, Progress report 2004–2005.
[5] Ullmann's Encyclopedia of Industrial Chemistry, 5th ed. A12 Weinheim, 1989. p. 186–204.
[6] Ullmann's Encyclopedia of Industrial Chemistry, 5th ed. A13 D6940 Weinheim, 1989. p. 311–28.
[7] Docekal J. Hydrogen production from hydrocarbons. Int J Hydrogen Energy 1986;11:709–14.
[8] Kothari Richa, Buddhi D, Sawhney RL. Sources and technology for hydrogen production: a review. Int J Global Energy Issues 2004;21(1 & 2):154–78.
[9] Bockris Jo'm. Energy—the solar-hydrogen alternative. London: The Architectural Press; 1975. pp. 44–56.
[10] Turner JA. A realizable renewable energy future. Science 1999;285:687–9.
[11] Kothari R, Buddhi D, Sawhney RL. Int J Hydrogen Energy 2005;30:261–3.